Energy Research and Development Division
FINAL PROJECT REPORT

IMPROVED STANDARDS THROUGH END-USE METER DEVELOPMENT

National Lab Buildings Energy Efficiency Research Projects

Prepared for: California Energy Commission
Prepared by: Lawrence Berkeley National Laboratory

JANUARY 2014
CEC-500-2014-096

BERKELEY LAB
Lawrence Berkeley National Laboratory

PREPARED BY:

Primary Author(s):

Steven Lanzisera
Richard Brown
Anna Liao
Margarita Kloss

Lawrence Berkeley National Laboratory
1 Cyclotron Road, MS2000
Berkeley, CA 94720
Phone: 510-486-4740 | Fax: 510-486-4673

Contract Number: 500-10-052

Prepared for:

California Energy Commission

Bradley Meister, Ph.D., P.E.
Project Manager

Heather Bird
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

LEGAL NOTICE

DISCLAIMER

The government and the facility operator make no express or implied warranty as to the conditions of the research or any intellectual property, generated information, or product made or developed under this agreement, or the ownership, merchantability, or fitness for a particular purpose of the research or resulting product: that the goods, services,. materials, products, processes, information, or data to be furnished hereunder will accomplish intended results or are safe for any purpose including the intended purpose; or that any of the above will not interfere with privately owned rights of others. Neither the government nor the facility operator shall be liable for special, consequential, or incidental damages attributed to such research or resulting product, intellectual property, generated information, or product made or delivered under this agreement.

ACKNOWLEDGMENTS

This work was supported by the California Energy Commission, Public Interest Energy Research Program, under Agreement No. 500-10-052.

The project team at Lawrence Berkeley National Laboratory would like to thank the sponsor, the Public Interest Energy Research Program of the California Energy Commission, Heather Bird, Chris Scruton, and especially the Program Manager, Brad Meister.

Thanks to the following individuals who contributed to this work:

- Lawrence Berkeley National Laboratory (LBNL) staff: Jim Lutz and Paula Ashley.
- Thanks, also, to our reviewers for their generosity and time improving this report.

Thanks to the many industry professionals who shared their ideas and feedback for this project.

LBNL especially thank the sites who participated in our study.

PREFACE

The California Energy Commission's Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Improved Standards Through End-Use Meter Development is the final report for the National Lab Buildings Energy Efficiency Research Projects (contract number 500-10-052) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Consumers today can buy an appliance electricity meter for $25 and estimate how a device's energy use impacts their energy bill. There are no equivalent products in the gas and water spaces. Currently, gas smart meters provide daily energy use, and water is billed at best monthly across the state. To fill the information gap, Lawrence Berkeley National Laboratory developed higher-resolution and low-cost water and gas metering technologies to better understand use of these resources and create effective strategies to save gas and water.

The water meter uses a turbine method of flow measurement and is able to work over a relatively large flow range, requires simple electronics, and has virtually no standby power when there is no water flow. Lawrence Berkeley National Laboratory developed a whole building gas meter with low cost and easy installation. Due to their non-invasive nature, the gas meters are likely to be readily accepted by the homeowner. The researchers created a cloud-based ecosystem for data management and real-time data reporting, so that consumers can easily use the technology.

Feedback to consumers on their electricity use reduces consumption by about 10 percent in residential settings. This figure requires more experimental validation, however, it can be reasonable to expect 5-10 percent savings through feedback on gas use. Market penetration at 5 percent savings across all residential natural gas use would realize more than $200 million in savings to California ratepayers annually. This project developed the prototype meters; however to achieve full energy savings potential will require commercialization. In addition to direct consumer energy savings, the data collected in future metering studies will have significant impact on building codes, appliance energy standards, and energy forecasts. These tools lead to significant energy savings or are critical for policy decisions.

Keywords: Water end-use meter, whole building gas meter, natural gas meter, wireless data collection system

Please use the following citation for this report:

Lanzisera, Steven; Anna Liao; Andrew Weber; Margarita Kloss; Richard Brown. (Lawrence Berkeley National Laboratory). 2014. ***Improved Standards Through End-Use Meter Development.*** California Energy Commission. Publication number: CEC-500-2014-096.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Consumers today can buy an inexpensive appliance electricity meter (e.g. a Kill-A-Watt) for $25 to estimate how a device's energy use impacts their energy bill. There are no equivalent products in the gas and water spaces, so using these resources are not easy to understand. Currently, gas smart meters provide daily energy use, and water is billed, at best, monthly throughout the state (although some forward looking water districts are piloting smart water meters in California). To fill the information gap, this project evaluates higher-resolution and low-cost water and gas metering technologies for use in California residences.

Project Purpose

Lawrence Berkeley National Laboratory (LBNL) developed basic tools necessary to obtain end-use metering information for gas and water end-uses in homes. This information can be used to inform end-use studies, energy efficiency standards, and other efforts to control and reduce energy consumption.

Project Results

LBNL developed a new, low-power, low-cost, end-use water meter for use in a hot water field study in California homes. The meters measure flow rate and water temperature, and wirelessly transmit data to a cloud-based data management system. This meter uses 100x less power than meters on the market, enabling a year of battery powered operation in the field.

Figure ES-1 shows a fully assembled meter as well as some of the components used to make the meter. The assembled meter has a printed circuit board (PCB) with a black connector protruding above the top of the unit (top left meter in Figure ES-1). The thin wire visible to the right of the connector joins a temperature sensor which contacts the water passing through the meter. The unassembled meter (meter plus components at bottom of Figure ES-1) shows the black turbine insert and the retainer that was added to hold the insert in place. More than 250 of these meters have been installed in California homes as part of a field study on residential hot water use.

Figure ES-1: End-use water meter developed as part of this project

Source: LBNL

The researchers developed a whole house gas meter that is very low-cost to build and install. This meter consists of a camera that takes photos of the meter face and a signal processing software which extracts the meter dial position (Figure ES-2). The changes in meter dial position from one image to the next provide the flow information. The entire meter is built with about $100 in off-the-shelf parts and can be assembled and installed in minutes. The most complicated part of the installation is connecting the meter to WiFi so that it can report data in real-time to a cloud-based data management system.

Figure ES-2: Non-intrusive gas meter installed on a PG&E SmartMeter

Source: LBNL

In the third element of this project, LBNL developed a data reporting and management system for energy field studies. This system includes WiFi and mesh network data collection methods for field study buildings as well as a cloud-based data management framework. LBNL leveraged existing tools that were either commercially available or available through open source software licenses.

Project Benefits

Californians spend $4.5 billion annually on residential natural gas, with an average household spending about $500 each year (http://energyalmanac.ca.gov). Natural gas is used in a variety of appliances including furnaces, water heaters, stoves, fireplaces, and clothes dryers. Although gas smart meters are being deployed by utilities, they do not provide data with high enough resolution or fine enough sampling rate to be useful for specific, actionable recommendations to reduce gas use. Gas is used in appliances to provide a service, such as provide warm water, space heating, or heat to dry clothes. There is a disconnect between the service provided to the consumer and the gas consumption, cost and carbon emissions associated with receiving that service. This project developed a gas meter that could be installed by a consumer to receive feedback on how changes in behavior or appliance upgrades impact their utility bills.

Feedback to consumers on their electricity use reduces consumption by about 10 percent in residential settings. This figure requires more experimental validation, it seems reasonable to expect 5-10 percent savings through feedback on gas use. Achieving 5 percent savings across all residential natural gas use would result in more than $200 million in savings to California ratepayers annually. This would require 100 percent market penetration, but even a 10 percent market penetration could lead to tens of millions of dollars of savings. This project developed prototype meters rather than a finished product, so the energy savings potential requires commercialization to be achieved. In addition to direct consumer energy savings, this technology will be useful for energy research even before commercialization. The data collected in future metering studies will have significant impact on building codes, appliance energy standards, and energy forecasts. These tools lead to significant energy savings or are critical for policy decisions.

The research described in this report is the result of Task 2.2, Improved Standards Through End-Use Meter Development, of the National Lab Buildings Energy Efficiency Research Projects, CEC Award No. 500-10-052.

CHAPTER 1: Project Overview and Motivation

Today consumers can buy an inexpensive appliance electricity meter (e.g. a Kill-A-Watt) for $25 and use it to estimate how a device's energy use impacts their energy bill. There are no equivalent products in the gas and water spaces, so the use of these resources is not easy to understand. Currently in California, gas smart meters provide daily energy use, and water is billed at best monthly across the state. Some forward looking water districts, however, are piloting smart water meters in California. To fill the information gap, this project evaluates higher-resolution and low-cost water and gas metering technologies for use in California residences.

Californians spend $4.5 billion annually on residential natural gas, with an average household spending of about $500 each year (http://energyalmanac.ca.gov). Natural gas is used in a variety of appliances including furnaces, water heaters, stoves, fireplaces, and clothes dryers. Although gas smart meters are being deployed by utilities, they do not provide data with high enough resolution or fine enough sampling rate to be highly useful. This project developed prototype gas meters that could be installed by a consumer to receive feedback on how changes in behavior or appliance upgrades would impact their utility bills. In addition, currently available gas submeters have a large form factor; a small one is approximately 8″x 8″x 8″ and too large to fit behind an appliance. This large physical size limits the ability to do definitive end-use metering and inform public policy. Researchers could use a meter developed in this task to generate high resolution whole building gas use traces, and software disaggregation tools will provide end-use data without the use of bulky submeters at each appliance.

Understanding and reducing water use and the corresponding energy used to heat wasted water is another significant issue for California. Available water flow and temperature sensors are too costly and energy expensive for use in most field studies. Available meters would either limit the length of studies to days or require mains power. In this project Lawrence Berkeley National Laboratory (LBNL) developed a low-power and low-cost water flow and temperature sensor to use in field studies on water use.

Collecting data in real-time is limits consumer and research applications of field metering. This task evaluates the needs for automated data collection and considers systems that are capable of filling these needs. LBNL select system components and fill in missing pieces for a cloud-based data management system where data are passed to the cloud over the Internet at the time the measurements are taken.

This study provides a review of gas and water metering technologies available on the market or in published academic literature, and also includes a discussion of the designs of water and gas meters. In a parallel project (Task 2.7), LBNL developed and are using an end-use water metering system to measure hot water distribution efficiency in California homes, and Task 2.2 supported this effort to develop custom, low-cost, wireless water meters suitable for the field study. Due to the contributions of the related work in Task 2.7, this task also developed a gas meter system. Chapter 2 reviews metering technology options that were explored. Chapters 3 and 4 describe the design of a water end-use meter and a whole house gas meter, respectively. Chapter 5 profiles the wireless data collection system, and the report finishes with a chapter on Conclusions and Next Steps.

CHAPTER 2:
Metering Technology Options

Measuring the flow of a fluid, whether a liquid or a gas, can be accomplished through mechanical, optical, or inferred means. A mechanical meter has the fluid push a rotor or operate a bellows-type damper by allowing for a pressure drop across the meter to drive the mechanical action of the meter. An optical meter accurately measures flow by measuring the scattering of the species. Meters that infer flow include: a) pressure-based sensors that use the Bernoulli effect to estimate flow based on known or modeled geometries of a system, and b) thermal type meters that heat the fluid and measure downstream temperature to estimate flow. All of these meters present advantages and disadvantages for consideration when fielding a meter for a particular application. A summary of the flow meter types and presents some advantages and disadvantages of each type.

Table 1: Summary of Flow Meters

Meter Type	Description of operation	Advantages	Disadvantages
Displacement	Gas flow fills and empties a set of bellows where each fill cycle represents a constant flow	Very accurate, good turn down ratio, no electrical power (purely mechanical)	Physically large
Thermal	Sensor measures the heat transfer off an element. Heat transfer is used as a way to estimate flow rate.	Able to measure small flows with moderate temporal resolution. No moving parts and minimal pressure drop.	Only for gas flow measurement, expensive for most applications. Point measurement in the flow rather than average over an area.
Turbine	Fan blades spin with flow of the fluid, and rotation speed is measured.	Inexpensive, easy to build, relatively small.	Sensitive to upstream flow geometry. Less accurate than displacement. Moderate turn down ratios (10:1).
Ultrasonic	Travel time of sound in a fluid is affected by the speed of the fluid.	Very accurate and does not obstruct the flow resulting in minimal pressure drop.	Expensive and difficult to build. Affected by temperature, density, viscosity of the medium more than other meters.

Table 1 (con't): Summary of Flow Meters

Meter Type	Description of operation	Advantages	Disadvantages

Vortex	A sensor detects pressure oscillation in a flow chamber where the oscillation frequency is proportional to flow rate.	Modular, inexpensive, easily replaced, and can overate over wide temperature ranges.	Need sufficient force (density and flow rate) to generate turbulent flow large enough to be measured. Poor intermittent flow accuracy.
Venturi	Sensor measures the pressure change in a tube due to gas flow.	Mechanically simple, no moving parts.	Poor turn down ratio. Pressure signal proportional to flow squared. Significant pressure drop at high flows.

Source: LBNL

In addition to the metering options shown in the table, other researchers have developed gas metering technologies. One particularly interesting example is the GasSense concept (Cohn, 2010). This work uses a microphone mounted to the utility gas meter's pressure regulator to detect sound from the regulator when gas is flowing. Using a training sequence of turning on different loads in the home, the researchers showed they could identify flow rate and end-use. Several challenges exist with making this system reliable, and these include dealing with significant background noise and changes in regulator characteristics with temperature and other weather conditions.

For the water meter, the turbine method of flow measurementwas selected because it is able to work over a relatively large flow range, requires simple electronics, and has virtually no standby power when there is no water flow. This last point is particularly important for battery operated sensors.

LBNL developed a whole building gas metering system that provides high flow-rate and temporal resolution suitable for end-use disaggregation and time-resolved gas use analysis. The gas utility provides a high quality, displacement-type gas meter at homes across California, and our metering system provides an automated way to read this meter every few seconds. This method was selected due to its low cost, easy installation, and probable acceptance by the homeowner. Disaggregating gas end uses is more straightforward than electricity, as gas involves fewer loads and the number and type of devices present rarely changes; also the loads can be distinguished by the pattern and quantity of gas consumed.

CHAPTER 3: Design of an End-use Water Meter

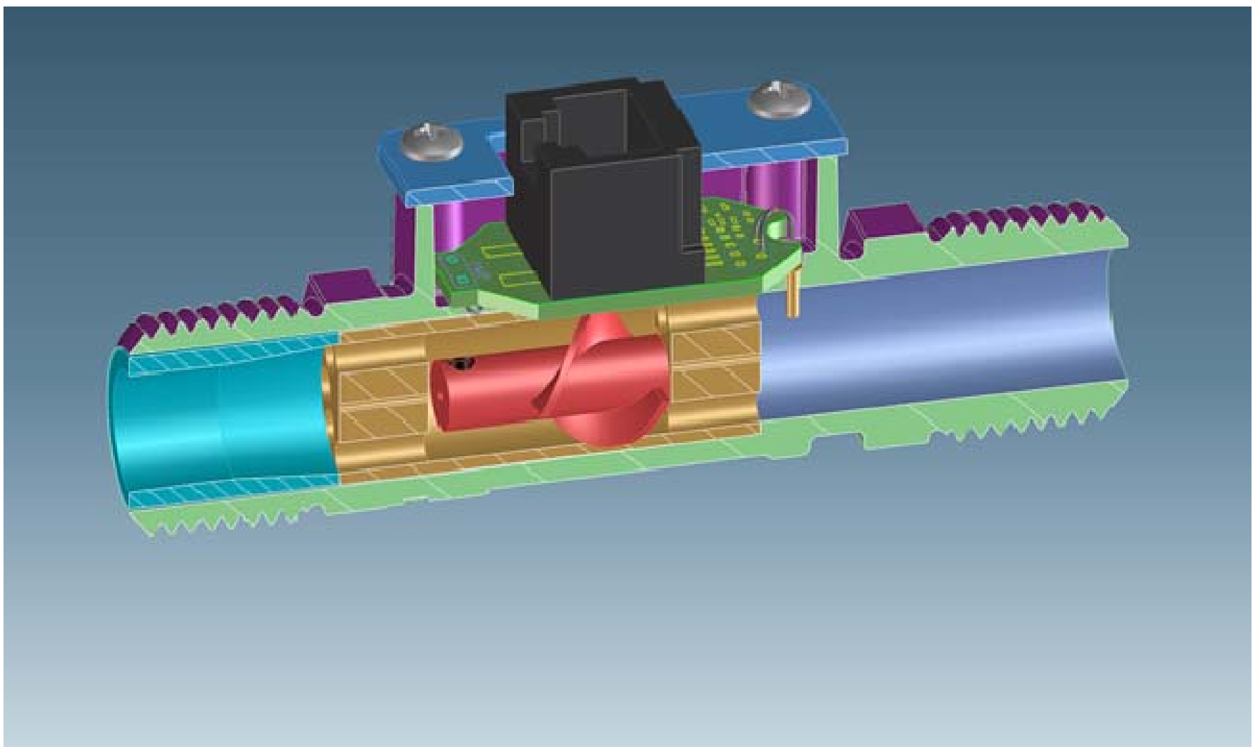
End-use water metering is rarely done in field studies in part because of poor availability of meters but also due to the high cost of available options. The typical variables of interest are flow rate and water temperature, but it is rare to find a meter that provides both of these variables in a single package. These existing meters and thermistors (shown in Figure 1) result in a system with poor robustness and less-than-appealing appearance coupled with high overall cost. Their measurement performance is acceptable for most end-use metering tasks, but they consume more power than can be supported using a typical battery for a multi-month field study. In the parallel field study to measure water end-use (Task 2.7), it was quickly found that meters on the market do not provide the low power performance necessary while also providing a visually appealing, robust package. LBNL, therefore, designed an integrated water meter package optimized for measuring flow and temperature data at water end uses in homes.

Figure 1: Predecessor water meter design

Source: LBNL

LBNL selected the turbine method of flow measurement because it is able to work over a relatively large flow range, requires simple electronics, and can have virtually no standby power when there is no water flow. This last point is particularly important for battery operated sensors. A flow turbine insert is available for purchase from Sika and Gems, and initially the Gems turbine was selected because it was lower cost. Gems, however, discontinued the production of the model for hot water use before the research team was able to purchase the quantity required, and the Sika unit was used instead. Sika specifies the geometry of the flow chamber, and the rest of the housing was custom designed. A 3D model of the design is shown (Figure 2) including the flow turbine, the housing, the electronics board, and the thermistor.

Figure 2: Flow turbine water meter design



Source: LBNL

The electronic interface recommended by Sika is a Hall effect sensor that detects the movement of the magnetic turbine insert. The part specified uses 5mA at 5V regardless of flow rate, and this is several orders of magnitude more than the microprocessor and radio used for data collection and wireless data communication. LBNL found that the best in class Hall effect sensor reduced this current by 10x to 0.5mA at 3V. However, all other aspects of the system consume 0.1mA at 3V, so the Hall effect sensor still dominated. The Hall effect sensor was replaced with a reed switch and a resistor. This combination uses current no more than half the time (typically only when there is water flow), and the active current is 0.05mA at 3V. This second 10x reduction in current (combined with the non-constant consumption) drove our decision.

For temperature measurement, the research team included the smallest potable water-safe thermistor assembly they were able to find at a reasonable price. US Sensor custom manufactured the thermistor assembly to our specifications. It is gold-plated (for water safety) and only 0.05” in diameter. This very small probe has high thermal conductivity and small thermal mass, resulting in a fast response to temperature changes. The thermistor is glued into the housing and into the water flow chamber using a potable water-safe adhesive. A high strength adhesive is epoxied on top of the glued-in thermistor to provide a high strength solution. The printed circuit board is conformally coated with silicone to make the electronics water-resistant and operable in a condensing humidity environment such as a bathroom with a shower.

LBNL fabricated 600 of these flow meters and have deployed more than 250 in the field homes used in Task 2.7. Before deploying, a series of tests were completed on the meters including a 500 psi stress test, a thermal cycling test where hundreds of hot/cold water thermal cycles at nominal domestic water pressure were completed, and tests of flow and temperature repeatability and accuracy. The flow sensors were found to have adequate repeatability and accuracy (better than 5 percent with 2 percent errors at one gallon per minute (GPM) being typical). Temperature sensor accuracy was found to be insufficient without calibration, and the sensors were individually calibrated using ambient temperature water and one elevated temperature around 100 degrees F. The absolute value of the two points was not important as long as they were sufficiently different.

The fabricated and assembled unit is being tested at standard domestic water pressure and at flows from 0.5 gallons per minute up to 5 gallons per minute (Figure 3). Two fitting types are shown: standard pipe thread (brass) and a flex-line which uses a gasket seal instead of a thread seal (chrome). The RJ45 connector and cable (grey) are the signal leads that go to the wireless module. We have also tested the meter with a static water pressure of 150psi for 15 minutes. Water heaters have a pressure relief valve set at 80psi to relieve over pressure in the line, and the highest transient water pressure heard of is 120psi due to water hammer. Therefore, the researchers believe this meter is robust. The meter was also tested up to 500psi for one minute to verify that it meets ASTM burst pressure standards for the worst case conditions.

Figure 3: Fabricated and assembled flow turbine water meter

Source: LBNL

CHAPTER 4:
Design of a Whole Building Gas Meter

A low-cost prototype whole building gas meter capable of gathering data at frequent intervals was built, which would allowed disaggregation software to distinguish between individual loads. The researchers wanted the meter to be easy to install by someone without specific plumbing, electrical, or networking expertise, and with little to no impact on the homeowner. Individual components of the system were also to be readily available, with little to no custom fabrication necessary.

Following these criteria, we designed and prototyped a low cost (less than $200) whole building gas meter that can be installed by nearly anyone. Its hardware and software design is easily replicated, and the data it records is granular enough to be disaggregated with software to reveal individual end use loads.

Figures 4 and 5 show the complete assembly of the gas meter, and the meter mounted to a PG&E SmartMeter.

Figure 4: Complete assembly

Source: LBNL

Figure 5: Meter mounted to PG&E SmartMeter

Source: LBNL

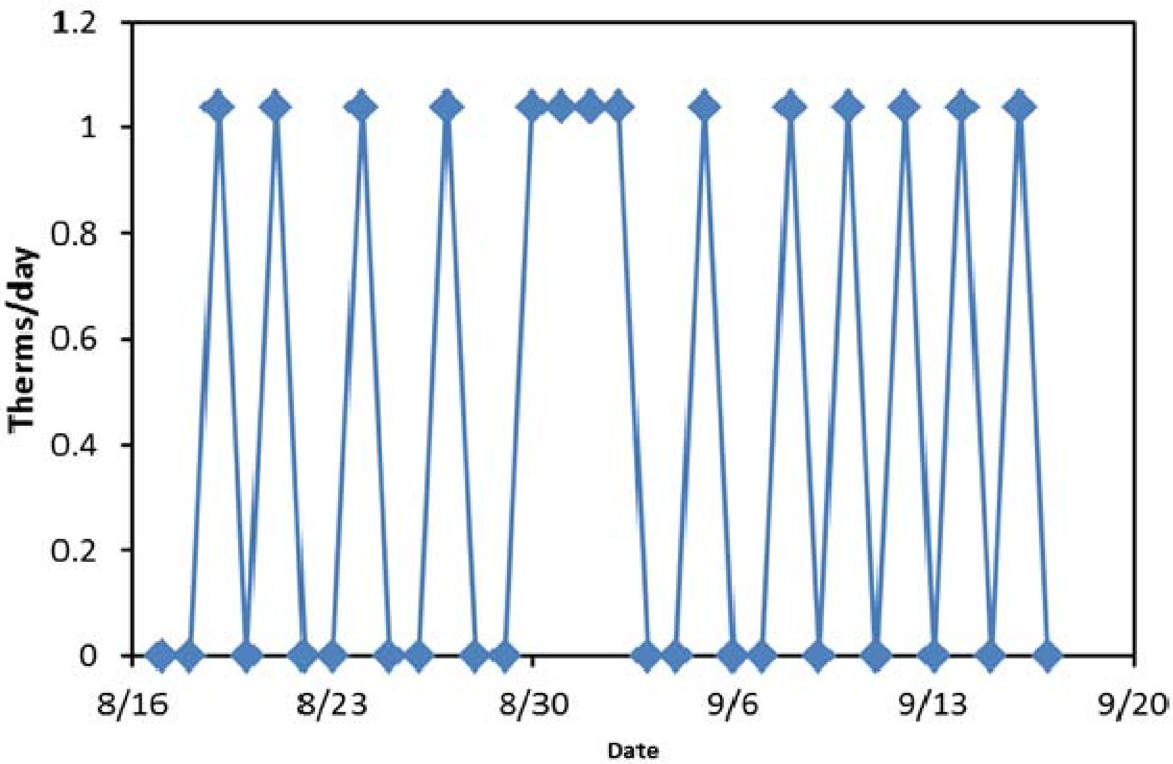
4.1 Comparison with other methods of gas metering and sub-metering and resulting design

Measuring gas use at the level of the individual appliance has several downsides that were identified, and sought to overcome with a whole building meter. First, expense rises quickly since a meter must be placed at each end device. Second, these devices would require professional installation due to the need to disconnect and reconnect gas connections in the home. Third, users perceive a level of danger when gas connections are manipulated, and electronic devices are installed. A whole building meter avoids these issues, keeps costs low, has a simple installation process, and is not considered invasive by the homeowner.

End device monitoring versus whole building monitoring and software disaggregation has become a popular discussion topic within energy monitoring circles. The pitfalls of using disaggregation techniques for electricity metering have been well documented. For example, devices that lack discrete power states (such as on or off) are difficult to distinguish from other loads. Our hypothesis is that this issue will be somewhat less prevalent with the disaggregation of residential whole building gas data. For one, there are fewer loads to consider and they are usually static, meaning that the number and type of devices present rarely changes. In addition, our initial analysis has revealed that the loads are relatively easy to distinguish from one another based on the pattern and quantity of gas they require to operate.

PG&E SmartMeters also measure gas consumption on a whole building level, but they do so at a frequency of once every 24 hours and at a resolution of 1 therm. This low frequency and data resolution make disaggregation impossible as there is no way to distinguish between loads. Example data provided to customers from gas smart meters is shown plotted in Figure 8. This shows one billing cycle of SmartMeter data, and it demonstrates the low resolution of these data. On alternating days the home is shown to have used either zero or one therms. A few times zero Therms were reported two days in a row, and once one therm was reported four days in a row. The actual use in any day was either zero or one Therm, but the resolution of the smart meter reporting coupled with a once a day sample period results in data that are difficult to interpret.

Figure 6: Example smart meter data presented to California ratepayers

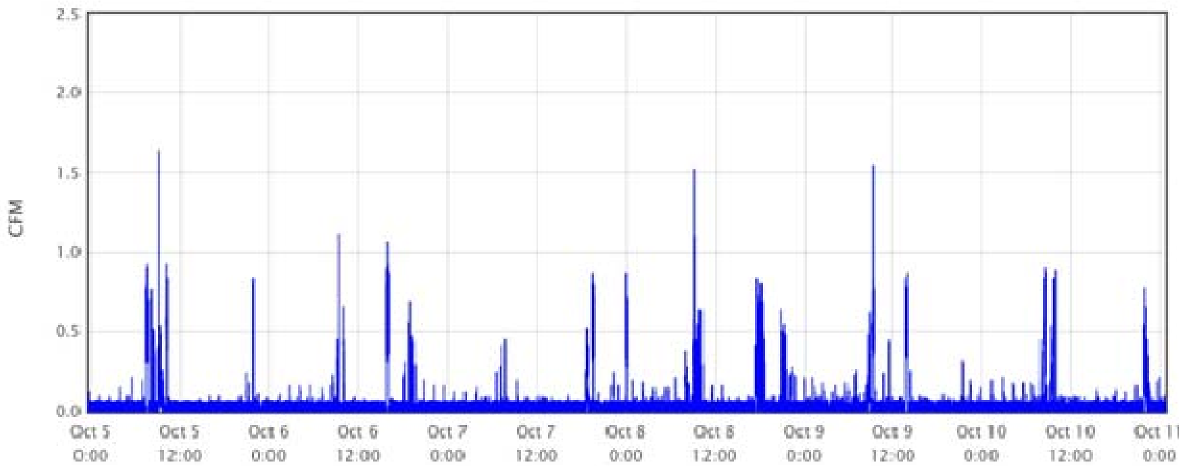


Source: LBNL

Taken together, these considerations make the case for a supplemental low-cost, whole building meter and associated disaggregation software. The researchers designed and built such a meter, capable of measuring gas use rates at 10 second intervals at a resolution of 0.5kBtu/h. This frequency and resolution will enable loads to be distinguished and disaggregation techniques to be applied. Initial analysis shows that distinguishing loads is possible with our meter.

The chart below (Figure 7) shows a high resolution gas data capture using the prototype meter. The units are different (cubic feet per minute or CFM vs. therms where one therm is approximately 100 cubic feet of gas), and the chart demonstrates the significant difference in data resolution.

Figure 7: One week of meter data



Source: LBNL

This higher data resolution allows the user to see what is using gas, and how much, in real time with an Internet-based data aggregation and plotting service. Data is archived in the cloud as it is reported, which eliminates the need for the meter to store data locally. The meter was designed to work with UC Berkeley's open source sMAP data aggregation and visualization system. The underlying software could be easily modified to report use data to another data source.

4.2 Components and Costs

To build the meter, components were selected that were low cost, open source (when possible), and easy to install. The ARM-based Raspberry Pi (RPi) is the main control entity for our meter. (See Figure 10.) Small, inexpensive, and relatively powerful embedded computers such as the RPi are increasingly available on the market. These devices nearly universally run a lightweight version of Linux, which makes the code developed for this project highly portable. A more powerful embedded computer could enable more frequent readings at a higher accuracy, further enhancing the viability of this type of whole building gas metering solution.

Figure 8: Raspberry Pi embedded Linux computer

Source: LBNL

The open source nature of the hardware, low cost, and variety of connectivity options make it a good fit for this project. The RPi was configured to run the Debian distribution of Linux. The meter control and data handling processes are handled by a combination of Linux shell scripts, and Python. A more detailed discussion of these processes can be found in the Software section of this report. The researchers configured the RPi to use a small USB WiFi adapter, which allows it to communicate with ther data management service over the user's home Internet connection.

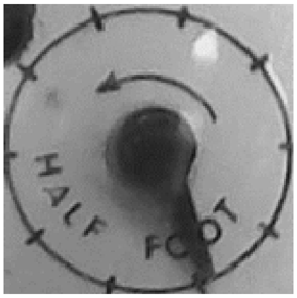
To read the meter, a USB endoscope camera (Figure 11) was used originally intended for pipe inspection. This turned out to be the ideal solution for these purposes because the camera was both weatherproof and self-lit, allowing the meter to be accurately read at night without additional hardware.

Figure 9: Weatherproof self-lit USB camera

Source: LBNL

The camera takes pictures at 640x480 resolution of the half foot dial on the gas meter. A full rotation of this dial (Figure 10) represents one half foot of gas usage in the home. By taking pictures of this dial at regular (12 second) intervals, researchers determineed the current rate of gas use.

Figure 10: Sample dial picture



Source: LBNL

A complete list of components, and associated costs below provide the 'one-off' purchases, and economies of scale would yield a lower unit cost when building large numbers of meters (Figure 11).

Figure 11: Components and associated costs

Component	Cost
Camera	$17
Embedded Computer	$35
WiFi Adapter	$10
Solid State Storage	$10
USB Hub	$6
Case	$20
Clamp	$8
Total	**$106**

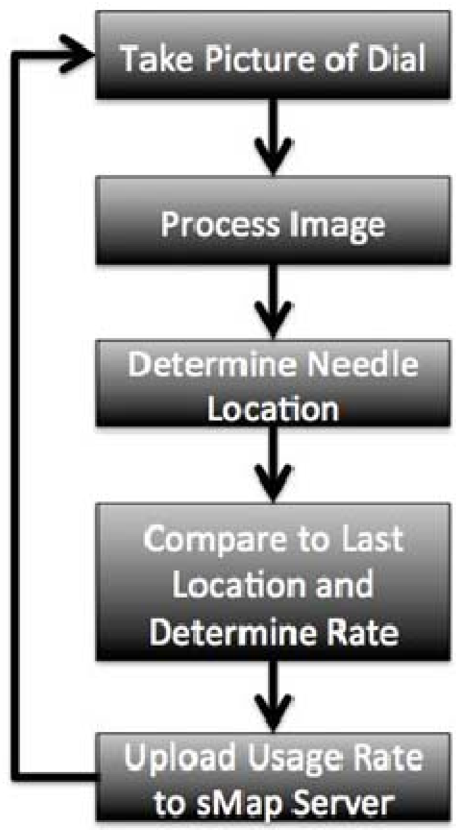
Source: LBNL

4.3 Software

The software running on the RPi is written to achieve a balance between frequent readings, and accuracy. All software is written in a Python script running on the RPi with the exception of the image capture process, which is run from a Linux shell script. The meter reading software begins upon boot, and can be pre-configured with the user's home WiFi information, minimizing setup burden. The software also runs a script every minute to determine if the meter reader is still connected to the home WiFi. If a connection interrupt is detected, the unit automatically reboots and attempts to reconnect.

A flowchart outlining the meter reading and analysis software is in Figure 12 below:

Figure 12: Software flow



Source: LBNL

A lightweight image capture utility (fswebcam) was used to take a picture of the meter's half foot dial. The image is then run through a series of filters in a python script to sharpen the contrast of the needle of the dial compared to the background (Figure 13).

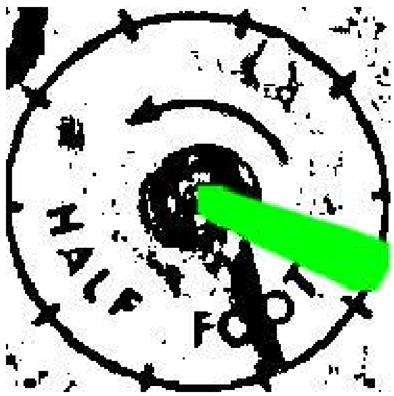
Figure 13: Dial after image processing

Source: LBNL

After this initial processing, the python script determines the dial's position. It does so through the use of an image mask. With this technique, a wedge-shape is rotated around the dial. At each location, the number of black pixels in the dial face are counted. The program assumes that when it finds the location with the most black pixels, it has found the location of the dial needle. This location (in degrees) is then stored. The following images (Figure 14) show a simulation of this angle determination technique. The green wedge represents the area where the program counts the number of black pixels. The dial's location should be where the most black pixels are located in the image.

Figure 14: Try - try - success!

Try --



Try --

Success!

Source: LBNL

By comparing consecutive dial locations and the time lapse between readings, we are able to determine the rate at which the dial is moving, and subsequently the rate of gas consumption in CFM.

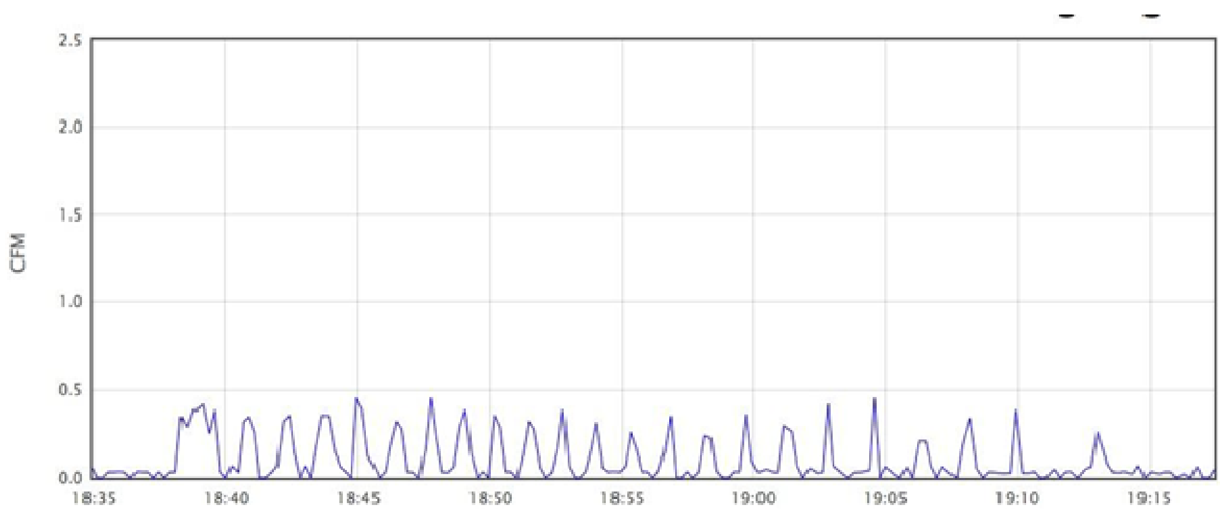
The script then uploads the current rate of consumption to the cloud-based data aggregation and visualization server (smap.lbl.gov). The data can be shown in real time on the website, or it can be used by an external service through the use of the sMAP API. Uploading and archiving usage data on this server allows the disaggregation component to run on a device outside of the user's home, allowing a lower-power computer such as the RPi.

4.4 Initial Analysis of Data and Opportunities for Future Work

An extensive work on the disaggregation component of the software development was not performed. The prototype meter, however, was used to collect enough data to indicate that continuing with the disaggregation effort will be worthwhile. In both homes where data was collected, the end use appliances generate distinctive load shapes. These unique load profiles should allow researchers to disaggregate individual appliances from the total usage.

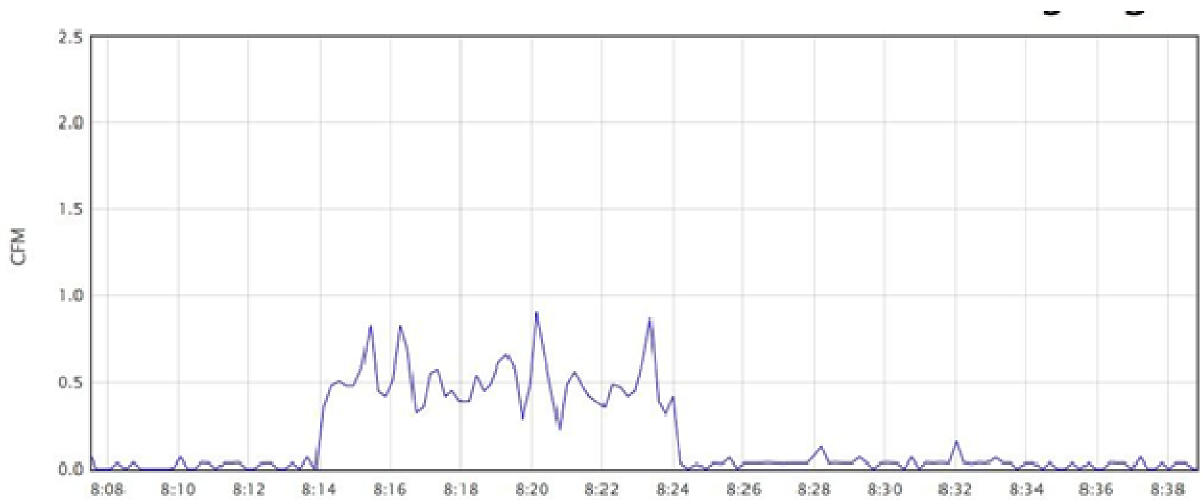
The graphs below show examples of these loads, labeled with the appliance that they represent. (Figures 15-18.)

Figure 15: Dryer



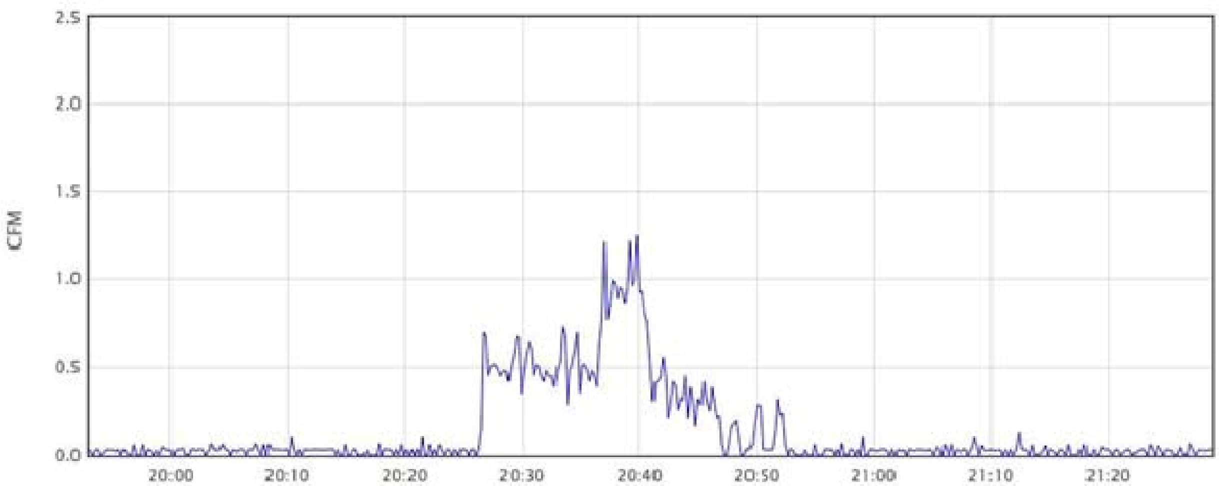
Source: LBNL

Figure 16: Hot water heater (shower)



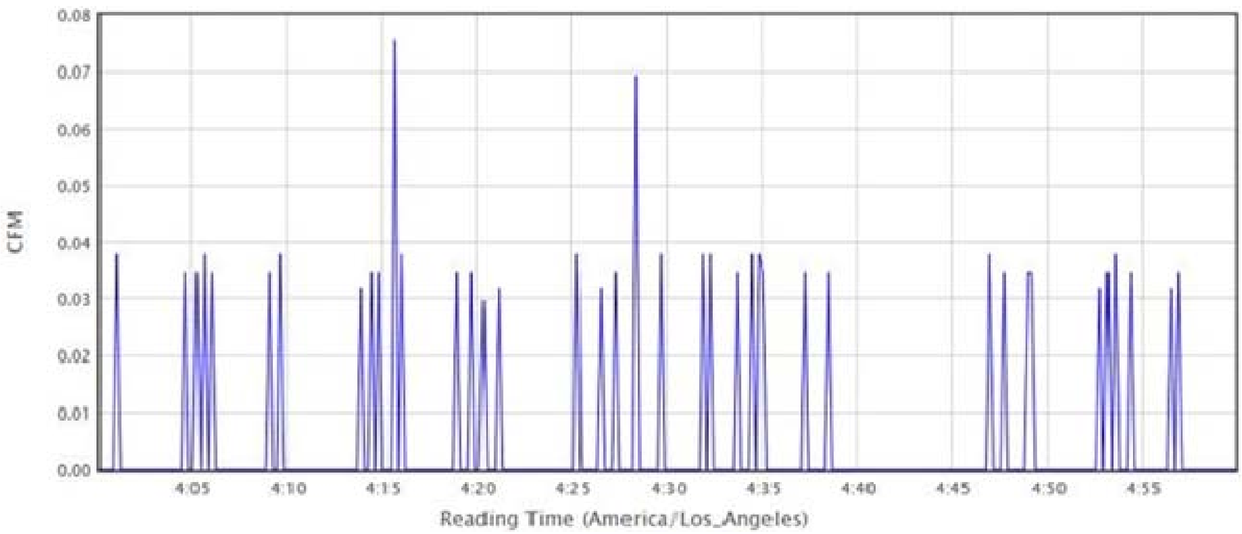
Source: LBNL

Figure 17: Stove (cooking)



Source: LBNL

Figure 18: Pilot light



Source: LBNL

More work is needed to develop a software solution to effectively disaggregate the data collected by the meter. Researchers believe that the current meter is capable of collecting data suitable for disaggregation, and that the individual loads have distinctive signatures conducive to disaggregation techniques. With further development, this software could work in parallel with the data collection system, enabling real-time remote analysis of what is using gas and how much is being consumed.

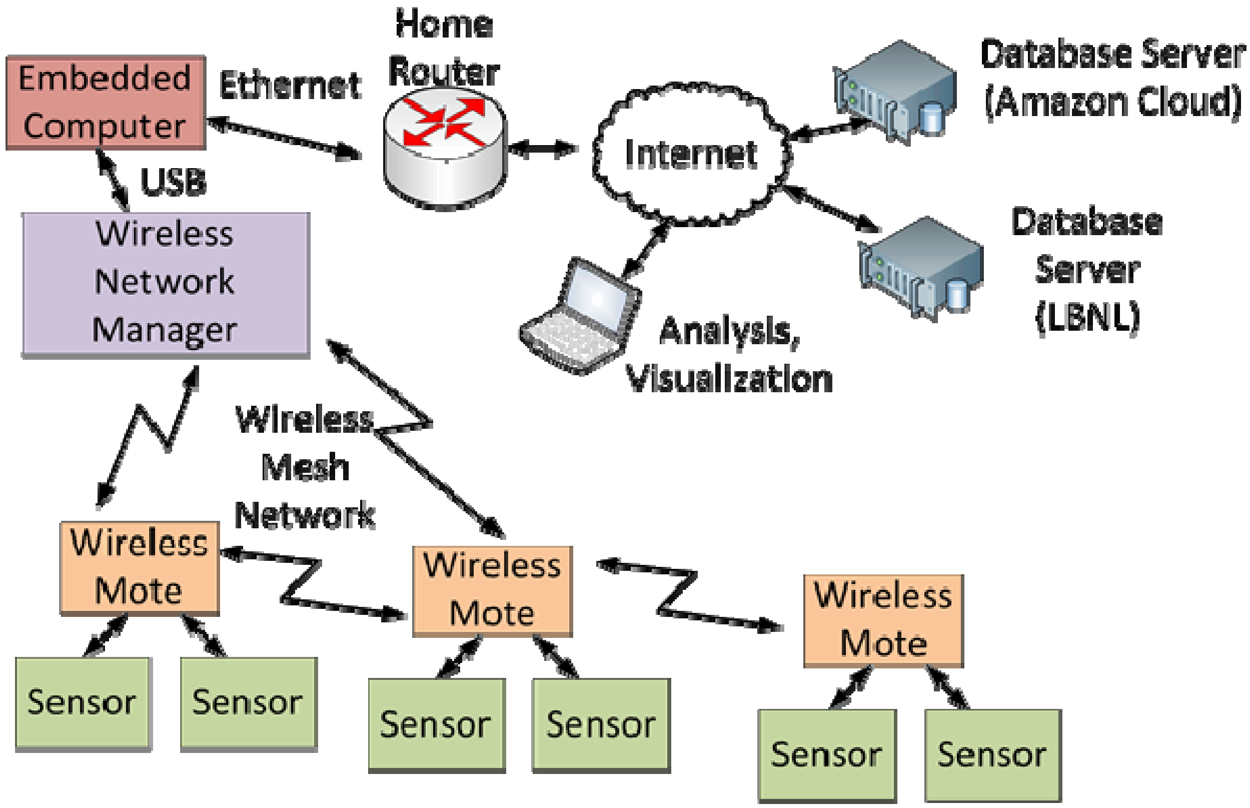
CHAPTER 5: Wireless Data Collection System

A crucial part of using low-cost sensors is the ability to access the data easily. This is true both for consumers and researchers because difficult data access limits people’s willingness to use the technology. There are two traditional solutions to collecting data over time: a) have a meter that integrates usage (like the meter that measures cubic feet of gas, only shows elapsed total usage), or b) use a meter that logs data at fixed intervals. In the first case, it is impossible to determine when the resource was used, and this limits the usefulness of the data. In the second case, the data logger must be connected to a computer, have data downloaded, and then plotted or analyzed. In research studies the additional labor is costly and prevents researchers from identifying and fixing problems in the data collection until after the next data download. For homeowners this process is too onerous to be completed in the margins of time available in peoples' busy lives.

An easy to use, cloud-based ecosystem for data management and real-time data reporting was created. The concept (Figure 21) shows the architecture for the water meter data collection system. The gas meter system replaces the wireless mesh network and manager with a WiFi connection directly to the home router but is otherwise the same. This system consists of many open source or licensed software components that, when combined with additional software to stitch the parts together, creates a complete system. The wireless mesh network used is available from Linear Technology as part of their SmartMesh IP product line. Linear sells wireless mote chips and licenses software to run on these chips for a complete network stack. Researchers used the Linear software and wrote an additional application that ran on their chip and interfaced to our sensors. An application was created to run on the manager, interface with the network, and post the resulting data to our Internet-based data management system. The data management system is UC Berkeley’s sMAP data historian tool, and was implemented in multiple locations for data redundancy. (Dawson-Haggerty, 2010)

This overall architecture has already been used in other projects, including a telemetry data management system for demand response, and for the gas meter data collection system described in this report. Closely related, derivative systems are being used for transactional control here at LBNL and at other national laboratories as a result of the initial work done in this project.

Figure 19: Conceptual drawing of data collection system



Source: LBNL

CHAPTER 6: Conclusions and Next Steps

New water and gas metering systems and a data collection framework were developed to manage meter data from these systems. All three of these components have been tested in field deployments, and both the water meter and the data collection system are actively being used in one or more projects at Berkeley Lab.

In the future, water meter applications could be expanded to save water and energy in the small and medium commercial, agricultural, and industrial sectors. The gas metering system would benefit from additional research on the automatic identification of the type of equipment using the gas so that end-use profiles could be generated from the whole-building gas flow data.

Feedback on electricity use has been shown to reduce usage by about 10 percent in residential settings, and, although this figure requires more experimental validation, it seems reasonable to expect 5 percent-10 percent savings through feedback on gas usage. Achieving 5 percent savings across all residential natural gas use would result in over $200M in savings to California ratepayers annually. This would require 100 percent market penetration, but even a 10 percent market penetration could lead to tens of millions of dollars of savings. This project aims to develop prototype meters rather than a finished product, so the energy savings potential requires commercialization to be achieved. In addition to direct consumer energy savings, this technology will be useful for energy research even before commercialization. The data collected in future metering studies will have significant impact on building codes, appliance energy standards, and energy forecasts. These tools lead to significant energy savings or are critical for policy decisions.

GLOSSARY

Term	Definition
API	Application programming interface
CFS	Cubic feet seconds
PCB	Printed circuit board

REFERENCES

Cohn, Gabe, Sidhant Gupta, Jon Froelich, Eric Larson, and Shwetak N. Patel. "GasSense: Appliance-Level, Single-Point Sensing of Gas Activity in the Home," In *Pervasive Computing*, Floréen, Patrik., Antonio Krüger, and Mijana Spasojevic, ed. pp. 265–282. Berlin Heidelberg: Springer-Verlag, 2010. Pdf e-book: http://download.springer.com/static/pdf/842/bok%253A978-3-642-12654-3.pdf?auth66=1390168096_3bc5a7482ec9de21d14082f62416d7e5&ext=.pdf, accessed 01.17.14.

Dawson-Haggerty, Stephen; Xiaofan Jiang; Gilman Tolle; Jorge Ortiz; and David Culler. "sMAP — a Simple Measurement and Actuation Profile for Physical Information." In *Proceedings of the Eighth ACM Conference on Embedded Networked Sensor Systems (SenSys '10)*, November 2010.